

# Study of anomalous top quark FCNC interactions via $tW$ -channel of single top

S. M. Etesami <sup>†,‡</sup>, M. Mohammadi Najafabadi <sup>‡,1</sup>

<sup>†</sup> *Physics Department, Isfahan University of Technology (IUT)*

*Isfahan, Iran*

and

<sup>‡</sup> *School of Particles and Accelerators,*

*Institute for Research in Fundamental Sciences (IPM)*

*P.O. Box 19395-5531, Tehran, Iran*

## Abstract

The potential of the LHC for investigation of anomalous top quark interactions with gluon ( $tug, tcg$ ) through the production of  $tW$ -channel of single top quark is studied. In the Standard Model, the single top quarks in the  $tW$ -channel mode are charge symmetric meaning that  $\sigma(pp \rightarrow t + W^-) = \sigma(pp \rightarrow \bar{t} + W^+)$ . However, the presence of anomalous FCNC couplings leads to charge asymmetry. In this paper a method is proposed in which this charge asymmetry may be used to constrain anomalous FCNC couplings. The strength of resulting constraints is estimated for the LHC for the center of mass energies of 7 and 14 TeV.

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<sup>1</sup>Corresponding author email address: mojtaba@ipm.ir

# 1 Introduction

Several properties of the top quark have been measured ever since its discovery [1–7]. However, there are still open questions whether the top quark couplings obey the Standard Model (SM) or there exist contributions from beyond Standard Model physics. One tool that is often used to describe the effects of new physics at an energy scale of  $\Lambda$ , much higher than the electroweak scale, is the effective Lagrangian method. If the underlying extended theory under consideration only becomes important at a scale of  $\Lambda$ , then it makes sense to expand the Lagrangian in powers of  $\Lambda^{-1}$  [8–10]:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^{n_i-4}} O_i \quad (1)$$

where  $\mathcal{L}_{SM}$  is the standard model Lagrangian,  $O_i$ 's are the operators containing *only* the SM fields,  $n_i$  is the dimension of  $O_i$  and  $c_i$ 's are dimensionless parameters. In the top quark sector, the lowest dimension operators that contribute to FCNC with the  $t c g, t u g$  vertex can be written as [2]:

$$g_s \frac{\kappa_u}{\Lambda} \bar{u} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G_{\mu\nu}^a + h.c. , \quad g_s \frac{\kappa_c}{\Lambda} \bar{c} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G_{\mu\nu}^a + h.c. \quad (2)$$

where  $g_s$  is the strong coupling constant,  $\kappa_{u,c}$  are free parameters determining the strength of these anomalous couplings and  $G_{\mu\nu}^a$  is the gauge field tensor of the gluon.  $\lambda_a$  are Gell-Mann matrices.  $u, c, t$  are Dirac spinors for up, charm and top quarks and  $\sigma_{\mu\nu} = i(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)/2$ . The presence of such anomalous FCNC vertices leads to additional processes in the  $tW$  channel mode of single top production at hadron colliders such as the LHC. Figure 1 shows the Feynman diagrams for the production of  $tW$  channel of single top in the SM framework and the new diagrams which are because of the new anomalous FCNC interactions introduced in Eq.2.

Single top quark in the  $tW$  mode is not observable at Tevatron because of its very small cross section. However, at the LHC the cross section of  $tW$  channel at leading order is around 62 pb. It has been shown that this process is observable at the LHC using the fully simulated data at the CMS and ATLAS detectors [11,12]. Recently, this process has been studied carefully in [13].

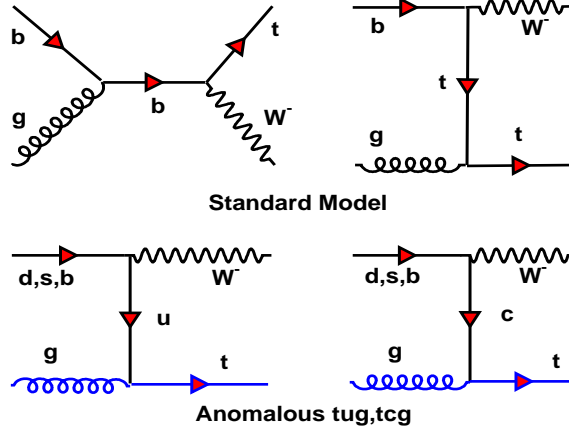


Figure 1: Feynman diagrams for the  $tW$  channel single top production at the LHC including anomalous FCNC vertices.

There are many experimental and phenomenological studies about FCNC anomalous couplings which some can be found in [14–46]. In the SM framework, the  $tW$  mode of single top is charge symmetric meaning that  $\sigma(pp \rightarrow t + W^- + X) = \sigma(pp \rightarrow \bar{t} + W^+ + X)$ . The reason is that the parton distribution functions (PDFs) of  $b$ -quark and  $\bar{b}$ -quark in proton are the same. According to Figure 1 in the presence of anomalous couplings, the  $d$ -quark contributes to the production of top quark and  $\bar{d}$ -quark contributes to the production anti-top quark. Since the parton distribution function of  $d$ -quark in the proton is more than the parton distribution function of  $\bar{d}$ -quark, the presence of anomalous FCNC vertices described by Eq.2 leads to an asymmetry of charge in the  $tW$  channel production. It is worth mentioning that the charge asymmetry in  $tW$ -channel can also be generated by non-SM values of  $V_{td}$  and  $V_{ts}$  of CKM (Cabibbo-Kobayashi-Maskawa) matrix [47].

The aim of this article is to benefit of charge asymmetry to estimate the limits for such anomalous couplings. Since the two main backgrounds in study of  $tW$  channel ( $t\bar{t}$ , QCD events and  $WW$ ) are charge symmetric, using charge asymmetry method is considered as a powerful tool to obtain the limits on anomalous FCNC couplings.

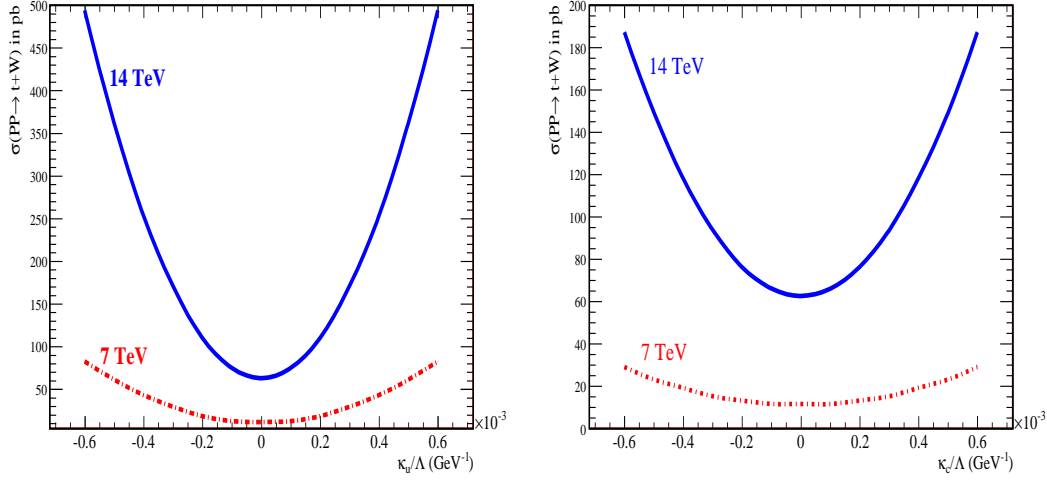


Figure 2: The  $tW$ -cross section dependence on the anomalous couplings at the LHC with the center of mass energies of 7 TeV and 14 TeV when  $\kappa_c = 0$  in the left side and when  $\kappa_u = 0$  in the right side.

## 2 The $tW$ -channel cross section and charge asymmetry sensitivities to anomalous couplings

The dependency of the  $tW$ -channel of single top quark cross section on the anomalous FCNC couplings ( $\kappa_{u,c}$ ) at the LHC with center of mass energies of 7 TeV and 14 TeV are presented in figure 2. This figure has been obtained using the CompHEP package [48]. In calculation of the cross section, it is assumed that  $m_{top} = 175 \text{ GeV}/c^2$ ,  $m_b = 4.8 \text{ GeV}/c^2$  and CTEQ6L1 is used as the proton parton distribution function. The CKM mixing angles are taken as:  $c_{12} = 0.97484$ ,  $c_{23} = 1.0$ ,  $c_{13} = 1.0$ .

According to CMS Collaboration full simulation results, the relative statistical uncertainty on measurement of the cross section ( $\frac{\Delta\sigma}{\sigma}$ ) of the  $tW$ -channel taking into account  $10 \text{ fb}^{-1}$  of integrated luminosity is 9.9% [11]. While ATLAS Collaboration predicted 2.8% for this value with  $30 \text{ fb}^{-1}$  of integrated luminosity of data [12]. Therefore, the cross section of the  $tW$  channel will be measured precisely by the LHC experiments.

In the SM, the cross section of single top quark and single anti-top quark in the  $tW$

channel mode are equal. Therefore:

$$R_{SM} = \frac{\sigma(pp \rightarrow t + W^-)}{\sigma(pp \rightarrow \bar{t} + W^+)} = 1. \quad (3)$$

However, when the anomalous FCNC vertices are taken into account the above ratio is not equal to one anymore and  $R = R(\kappa_u, \kappa_c)$ . Figure 4 presents the dependency of  $R$  on  $\kappa_u, \kappa_c$  at the LHC with the center of mass energies of 10 TeV and 14 TeV when  $\kappa_c = 0$  in the left side and when  $\kappa_u = 0$  in the right side. Due to the higher PDF contributions of the valence quarks w.r.t sea quarks in proton and the size of the involved CKM matrix elements in the new additional processes in the production of  $tW$  channel single top,  $R$  is more sensitive to  $\kappa_u$  with respect to  $\kappa_c$ . For example at the center of mass energy of 14 TeV:

$$\begin{aligned} R(\kappa_u/\Lambda = 0.2 \text{ TeV}^{-1}, \kappa_c/\Lambda = 0.0) &= 1.67 \\ R(\kappa_u/\Lambda = 0.0, \kappa_c/\Lambda = 0.2 \text{ TeV}^{-1}) &= 1.04 \end{aligned} \quad (4)$$

Therefore, any observable deviation of  $R$  from the SM expectation (charge asymmetry) can be exploited to predict the sensitivity to anomalous  $tug, tcg$  couplings. One should note that the advantage of using the ratio of  $R$  is that the uncertainties coming from parton distribution function, luminosity and etc. will cancel.

### 3 Monte Carlo simulation

In order to predict the sensitivity to the anomalous  $tug, tcg$  couplings, we perform Monte Carlo event generation and a very raw detector simulation (no specific detector is considered). One has to take into account backgrounds, realistic detector effects and selection cuts. Obviously, a comprehensive analysis of all reducible backgrounds and detector effects is beyond the scope of this study and must be performed by the experimental collaborations. In this study the anomalous single top signal events have been generated by CompHEP package [48]. The CompHEP-PYTHIA interface package [49] was used

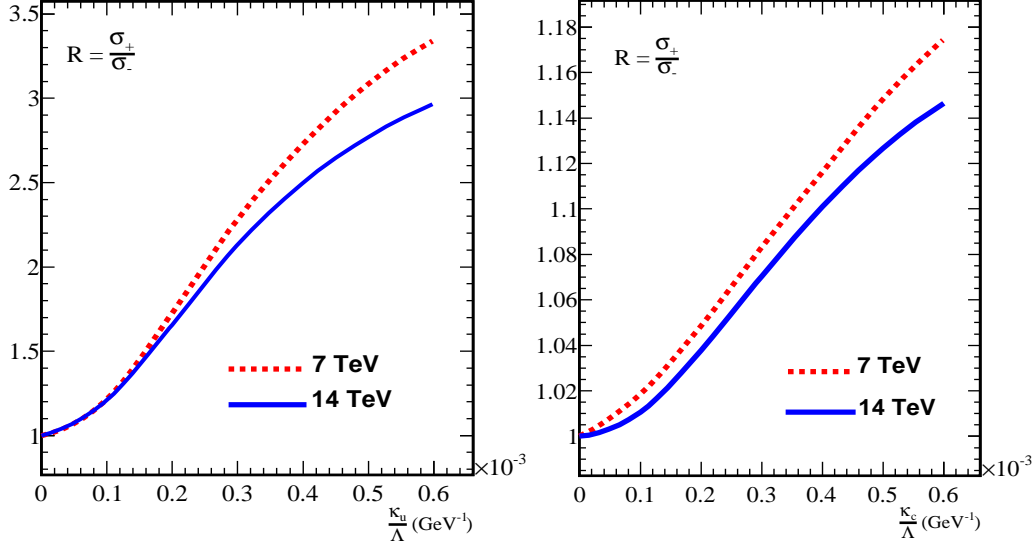


Figure 3: The ratio of cross section of top to anti-top in  $tW$ -channel versus  $\kappa_u, \kappa_c$  at the LHC with the center of mass energies of 7 TeV and 14 TeV when  $\kappa_c = 0$  in the left side and when  $\kappa_u = 0$  in the right side.

to pass the generated events through PYTHIA [50]. PYTHIA performs fragmentation, parton showering and hadronization.

The detector simulation is performed by smearing energies for stable particles deposited into proper segmentation of calorimeter geometry. A jet is clustered by PYCELL routine in PYTHIA with the cone size of 0.5. B-tagging is simulated with the efficiency of 60%. The missing transverse energy is calculated by the vector summation of the lepton and jets.

## 4 Event selection and sensitivity study

In this section after event selection, we predict the bounds on the anomalous FCNC vertices ( $tug, tcg$ ) using the *semi-leptonic* reconstructed events of  $tW$ -channel. One should note that by semi-leptonic we mean that the  $W$ -boson coming from the top decays to leptons and another  $W$ -decays to two jets. The final state consists of a charged lepton,

missing energy, and three hadronic jets.

To help reduce the backgrounds, we follow the strategy which ATLAS experiment proposed [2], [12]. In this strategy one isolated lepton (electron, muon) is required with transverse momentum<sup>2</sup> greater than 20 GeV/c and  $|\eta| < 2.5$ <sup>3</sup>. The number of jets in the central region ( $|\eta| < 2.5$ ) is required to be exactly three, each with  $p_T > 50$  GeV/c. One of the jets should be tagged as a b-jet. The requirement of at least one b-jet is necessary to reduce  $W + jets$  background events.

To ensure that the other two untagged jets come from the  $W$ -boson (which is not from top), it is required that the invariant mass of the two jets should satisfy:  $65 \text{ GeV}/c^2 < m_{jj} < 95 \text{ GeV}/c^2$ . It is noticeable that this cut and the cut on the number of jets are very useful to suppress the  $W + jets$  background [2]. It is also required that  $m_{l\nu b} < 300 \text{ GeV}/c^2$  which help suppress  $W + jets$  background. In contrast to  $t\bar{t}$  background, the  $W + jets$  background is not charge symmetric. However, according to the proposed strategy by ATLAS collaboration [2], [12] which was followed in the current analysis the applied cuts which mentioned above are powerful in suppressing  $W + jets$  background events. These cuts reduce  $W + jets$  background to a negligible level.

Since the charge asymmetry measurement is used in the analysis, the decays of  $tW^- \rightarrow W^+bW^- \rightarrow l^+\nu_l bjj'$  and  $tW^- \rightarrow W^+bW^- \rightarrow jj'bl^-\nu_l$  must be kinematically distinguished. To guarantee that it is required:  $m_{bjj'} < 125$  or  $m_{bjj'} > 225 \text{ GeV}/c^2$ .

The *pseudoexperiments* are used for the evaluation of the statistical significance and including the systematic uncertainties. For the signal process 30,000 random numbers are drawn from a Gaussian distribution centered on the number of selected events. Further Gaussian smearing is applied in order to take into account the overall systematic uncertainty. Calling  $G(m, \sigma)$  a random number belonging to a Gaussian distribution with mean  $m$  and standard deviation  $\sigma$ , each pseudoexperiment gives:

$$N^\pm = G(N_{sel}^\pm, \sqrt{N_{sel}^\pm}) \times G(1, \Delta_{sys}), \quad (5)$$

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<sup>2</sup> $p_T = \sqrt{p_x^2 + p_y^2}$   
<sup>3</sup> $\eta = -\ln(\tan(\frac{\theta}{2}))$

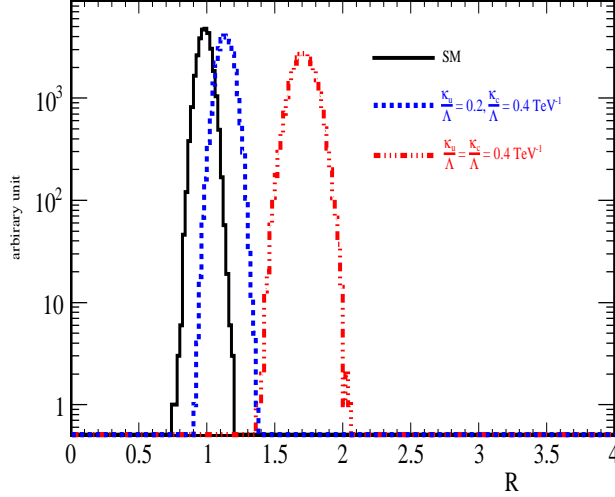


Figure 4: The outcome of the pseudoexperiments for  $R = \frac{N_+}{N_-}$  calculated from Eq.5 including 5% systematic uncertainty for the SM and for the presence of anomalous couplings.

where  $N_{sel}^\pm$  is the number selected of events after all cuts with positive and negative charge of the electrons or muons in the top quarks decay. As discussed before, several uncertainties will cancel when we use the ratio of  $R$  for the analysis. However, few sources of uncertainties may not cancel. Therefore  $\Delta_{sys}$  which is defined as an overall systematic uncertainty is included in the analysis to get more realistic results.

Figure 4 shows the outcome of the pseudoexperiments including 5% systematic uncertainty for  $R = \frac{N_+}{N_-}$  with center of mass energy of 14 TeV and  $10 \text{ fb}^{-1}$  of integrated luminosity. The signal significance is defined as:

$$S = \frac{M(\kappa_u, \kappa_c) - M_{SM}}{\sqrt{\sigma^2(\kappa_u, \kappa_c) + \sigma_{SM}^2}}. \quad (6)$$

where  $M$  is the peak position and  $\sigma$  is the standard deviation of the distributions.  $M$  and  $\sigma$  (for the SM case and the presence of anomalous couplings case) are extracted by Gaussian fits on the pseudoexperiments distribution in Figure 4. To determine the maximum allowed values of  $\frac{\kappa_u}{\Lambda}$  and  $\frac{\kappa_c}{\Lambda}$  that could be reached at the LHC, it is required that  $S > 5$  which is corresponding to approximately 68% confidence level. This requirement



	Tevatron 1.96 TeV, 2.2fb <sup>-1</sup>	LHC 7 TeV, 1fb <sup>-1</sup>	LHC 14 TeV, 10fb <sup>-1</sup>
$\kappa_u/\Lambda(2 \rightarrow 1) \text{ TeV}^{-1}$	0.018	-	0.003
$\kappa_u/\Lambda(2 \rightarrow 2) \text{ TeV}^{-1}$	0.037	-	0.006
$\kappa_u/\Lambda(tW) \text{ TeV}^{-1}$	-	0.1	0.08
$\kappa_c/\Lambda(2 \rightarrow 1) \text{ TeV}^{-1}$	0.069	-	0.008
$\kappa_c/\Lambda(2 \rightarrow 2) \text{ TeV}^{-1}$	0.15	-	0.013
$\kappa_c/\Lambda(tW) \text{ TeV}^{-1}$	-	0.38	0.35

Table 1: Limits on anomalous couplings obtained from various experiments and methods.

leads to the bounds on  $\frac{\kappa_u}{\Lambda}$  and  $\frac{\kappa_c}{\Lambda}$  separately presented in Table 1. It is noticeable that when the limit on  $\kappa_u$  is calculated  $\kappa_c$  is set to zero and vice versa.

The FCNC  $tqg$ -vertex has been studied via other processes such as quark-gluon fusion process  $u(c) + g \rightarrow t$  ( $2 \rightarrow 1$ ) or  $qq \rightarrow tq, gg \rightarrow t\bar{q}, qg \rightarrow tg$  ( $2 \rightarrow 2$ ) processes. The resulting limits from the studies of  $2 \rightarrow 1$  and  $2 \rightarrow 2$  processes with Tevatron data and LHC simulated data have been presented in Table 1 [36], [37]. One should note that the Tevatron bounds are at 95% confidence level. The estimated bounds from  $2 \rightarrow 1$  and  $2 \rightarrow 2$  are tighter than those obtained in this study. This is because of the larger cross sections and more statistics of these processes with respect to the  $tW$ -channel in the present study.

## 5 Conclusion

The  $tW$ -channel single top quark production at the LHC was considered as a probe for non-SM couplings at the LHC. In the SM, the cross section of single top quark and single anti-top quark in the  $tW$  channel mode are equal. Therefore,  $R_{SM} = \frac{\sigma(pp \rightarrow t+W^-)}{\sigma(pp \rightarrow \bar{t}+W^+)} = 1$ . However, when the anomalous FCNC vertices are taken into account the above ratio is not equal to one anymore and  $R = R(\kappa_u, \kappa_c)$ . This interesting aspect was used to extract

the 68% C.L. bounds on the anomalous couplings  $\frac{\kappa_{u(c)}}{\Lambda}$ . We find that at 14 TeV center of mass energy and with  $10 \text{ fb}^{-1}$  integrated luminosity of data:  $\frac{\kappa_{u(c)}}{\Lambda} = 0.08 \text{ TeV}^{-1}$  (0.35). The upper limits for 7 TeV center of mass energy with  $1 \text{ fb}^{-1}$  are:  $\frac{\kappa_{u(c)}}{\Lambda} = 0.1 \text{ TeV}^{-1}$  (0.38).

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## References

- [1] W. Bernreuther, J. Phys. G **35**, 083001 (2008) [arXiv:0805.1333 [hep-ph]].
- [2] M. Beneke *et al.*, arXiv:hep-ph/0003033.
- [3] T. M. P. Tait and C. P. P. Yuan, Phys. Rev. D **63**, 014018 (2001) [arXiv:hep-ph/0007298].
- [4] C. E. Gerber *et al.* [TeV4LHC-Top and Electroweak Working Group], arXiv:0705.3251 [hep-ph].
- [5] M. A. Pleier, arXiv:0810.5226 [hep-ex].
- [6] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 092002 (2009) [arXiv:0903.0885 [hep-ex]].
- [7] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **103**, 092001 (2009) [arXiv:0903.0850 [hep-ex]].
- [8] R. D. Peccei and X. Zhang, Nucl. Phys. B **337**, 269 (1990).
- [9] Z. Han, arXiv:0807.0490[hep-ph].

- [10] W. Buchmuller and D. Wyler, Nucl. Phys. B **268**, 621 (1986).
- [11] G. L. Bayatian *et al.* [CMS Collaboration], J. Phys. G **34** (2007) 995.
- [12] ATLAS Collaboration, ATLAS Physics TDR Vol. 2, CERN/LHCC/99-15.
- [13] C. D. White, S. Frixione, E. Laenen and F. Maltoni, JHEP **0911**, 074 (2009) [arXiv:0908.0631 [hep-ph]].
- [14] T. M. P. Tait and C. P. Yuan, Phys. Rev. D **55**, 7300 (1997) [arXiv:hep-ph/9611244].
- [15] T. Han, M. Hosch, K. Whisnant, B. L. Young and X. Zhang, Phys. Rev. D **58**, 073008 (1998) [arXiv:hep-ph/9806486].
- [16] J. M. Yang, arXiv:0801.0210 [hep-ph].
- [17] J. A. Aguilar-Saavedra, Acta Phys. Polon. B **35**, 2695 (2004).
- [18] J. A. Aguilar-Saavedra, Nucl. Phys. B **812**, 181 (2009) [arXiv:0811.3842 [hep-ph]].
- [19] R. A. Coimbra, P. M. Ferreira, R. B. Guedes, O. Oliveira, A. Onofre, R. Santos and M. Won, Phys. Rev. D **79**, 014006 (2009) [arXiv:0811.1743 [hep-ph]].
- [20] J. Carvalho *et al.* [ATLAS Collaboration], Eur. Phys. J. C **52**, 999 (2007) [arXiv:0712.1127 [hep-ex]].
- [21] A. A. Ashimova and S. R. Slabospitsky, Phys. Lett. B **668** (2008) 282, arXiv:hep-ph/0604119.
- [22] Yu. P. Gouz and S. R. Slabospitsky, Phys. Lett. B **457** (1999) 177, arXiv:hep-ph/9811330.
- [23] M. M. Najafabadi and N. Tazik, Commun. Theor. Phys. **52**, 662 (2009) [arXiv:0902.0441 [hep-ph]].
- [24] F. Larios, R. Martinez and M. A. Perez, Phys. Rev. D **72**, 057504 (2005) [arXiv:hep-ph/0412222].

- [25] J. Abdallah *et al.* [DELPHI Collaboration], Phys. Lett. B **590**, 21 (2004) [arXiv:hep-ex/0404014].
- [26] G. A. Gonzalez-Sprinberg and R. Martinez, arXiv:hep-ph/0605335.
- [27] J. Cao, Z. Heng, L. Wu and J. M. Yang, arXiv:0812.1698 [hep-ph].
- [28] J. A. Aguilar-Saavedra and B. M. Nobre, Phys. Lett. B **553**, 251 (2003) [arXiv:hep-ph/0210360].
- [29] S. Bejar, J. Guasch, D. Lopez-Val and J. Sola, Phys. Lett. B **668**, 364 (2008) [arXiv:0805.0973 [hep-ph]].
- [30] S. Bejar, J. Guasch and J. Sola, JHEP **0510**, 113 (2005) [arXiv:hep-ph/0508043].
- [31] J. A. Aguilar-Saavedra, [arXiv:1003.3173[hep-ph]].
- [32] G. Eilam, J. L. Hewett and A. Soni, Phys. Rev. D **44** (1991) 1473 [Erratum-ibid. D **59** (1999) 039901].
- [33] B. Mele, S. Petrarca and A. Soddu, Phys. Lett. B **435** (1998) 401 [hep-ph/9805498].
- [34] J. A. Aguilar-Saavedra and B. M. Nobre, Phys. Lett. B **553** (2003) 251 [arXiv:hep-ph/0210360]; F. del Aguila, J.A. Aguilar-Saavedra and L. Ametller, Phys. Lett. B **462** (1999) 310 [arXiv:hep-ph/9906462]; F. del Aguilar and J. A. Aguilar Saavedra, Nucl. Phys. B **576** (2000) 56 [arXiv:hep-ph/9909222].
- [35] P. M. Ferreira, O. Oliveira and R. Santos, Phys. Rev. D **73** (2006) 034011 [arXiv:hep-ph/0510087]; P. M. Ferreira and R. Santos, Phys. Rev. D **74** (2006) 014006 [arXiv:hep-ph/0604144]; P. M. Ferreira and R. Santos, Phys. Rev. D **73** (2006) 054025 [arXiv:hep-ph/0601078].
- [36] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **99**, 191802 (2007) [arXiv:hep-ex/0702005].
- [37] T. Aaltonen *et al.* [CDF Collaboration], arXiv:0812.3400 [hep-ex].

- [38] M. Hosch, K. Whisnant and B. L. Young, Phys. Rev. D **56**, 5725 (1997) [arXiv:hep-ph/9703450].
- [39] O. Cakir and S. A. Cetin, J. Phys. G **31**, N1 (2005).
- [40] M. Herquet, R. Kneijens and E. Laenen, arXiv:1005.2900 [hep-ph].
- [41] N. Kidonakis and A. Belyaev, JHEP **0312**, 004 (2003) [arXiv:hep-ph/0310299].
- [42] J. J. Liu, C. S. Li, L. L. Yang and L. G. Jin, Phys. Rev. D **72**, 074018 (2005) [arXiv:hep-ph/0508016].
- [43] J. J. Zhang, C. S. Li, J. Gao, H. Zhang, Z. Li, C. P. Yuan and T. C. Yuan, Phys. Rev. Lett. **102**, 072001 (2009) [arXiv:0810.3889 [hep-ph]].
- [44] J. J. Zhang, C. S. Li, J. Gao, H. X. Zhu, C. P. Yuan and T. C. Yuan, arXiv:1004.0898 [hep-ph].
- [45] J. Drobnak, S. Fajfer and J. F. Kamenik, arXiv:1004.0620 [hep-ph].
- [46] J. Drobnak, S. Fajfer and J. F. Kamenik, JHEP **0903**, 077 (2009) [arXiv:0812.0294 [hep-ph]].
- [47] J. A. Aguilar-Saavedra, A. Onofre, [arXiv:1002.4718[hep-ph]].
- [48] E. Boos *et al.* [CompHEP Collaboration], Nucl. Instrum. Meth. A **534**, 250 (2004) [arXiv:hep-ph/0403113].
- [49] A. S. Belyaev *et al.*, arXiv:hep-ph/0101232.
- [50] T. Sjostrand, S. Mrenna and P. Skands, JHEP **0605**, 026 (2006) [arXiv:hep-ph/0603175].
- [51] G. L. Bayatian *et al.* [CMS Collaboration], J. Phys. G **34**, 995 (2007).
- [52] F. Hubaut, E. Monnier, P. Pralavorio, K. Smolek and V. Simak, Eur. Phys. J. C **44S2**, 13 (2005) [arXiv:hep-ex/0508061].

- [53] J. A. Aguilar-Saavedra, J. Carvalho, N. F. Castro, A. Onofre and F. Veloso, Eur. Phys. J. C **53**, 689 (2008) [arXiv:0705.3041 [hep-ph]].
- [54] C. Amsler et al., Phys. Lett. B **667** (2008) 1.